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An Examination of Electric Fields Under EHV Overhead Power Transmission Lines

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AN EXAMINATION OF ELECTRIC FIELDS UNDER EHV OVERHEAD POWER TRANSMISSION LINES

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This report contains measured data on electric field strengths near ground level under 765 kV and 510 kV single circuit and 345 kV double circuit overhead power transmission lines, values of short circuit current originating on vehicles situated in relatively intense electric fields, and estimates of perception and annoyance for humans resulting from transient spark discharge. Calculated data is given for the electric field strength beneath 765 kV single circuit, 500 kV single circuit, and 345 kV single and double circuit lines.

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AN EXAMINATION OF ELECTRIC FIELDS UNDER EHV OVERHEAD POWER TRANSMISSION LINES

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April 1977

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DISCLAIMER

This report has been reviewed by the Office of Radiation Programs, U.S. Environmental Protection Agency, and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for their use.

PREFACE

The Office of Radiation Programs of the Environmental Protection Agency carries out a national program designed to evaluate population exposure to ionizing and nonionizing radiation, and to promote development of controls necessary to protect the public health and safety. This report describes the measurement of electric field strengths under extra-high voltage transmission lines and compares the measured values with analytical predictions. Readers of this report are encouraged to inform the Office of Radiation Programs of any omissions or errors.

W.D. Rowe, Ph.D.
Deputy Assistant Administrator
for Radiation Programs (AW-458)

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AN EXAMINATION OF ELECTRIC FIELDS UNDER EHV OVERHEAD POWER TRANSMISSION LINES

SUMMARY AND CONCLUSIONS

This report contains measured data on electric field strengths near ground level under 765 kV and 510 kV single circuit and 345 kV double circuit overhead power transmission lines, values of short circuit current originating on vehicles situated in relatively intense electric fields, and estimates of perception and annoyance for humans resulting from transient spark discharges. Calculated data is given for the electric field strength beneath 765 kV single circuit, 500 kV single circuit, and 345 kV single and double circuit lines.

The maximum measured electric field strength beneath the 765 kV line was approximately 10 kV/m at 3 feet above ground, occurring just outside the outer phase conductors. This value rises to about 12.5 kV/m at 6 feet above ground. The field strength decreases to 1 kV/m at approximately 170 feet from the center of the right-of-way (ROW) and to 100 V/m at approximately 360 feet from the ROW center. The maximum measured electric field strength beneath the 510 kV line was approximately 5 kV/m at about 3 feet above ground, occurring just outside the outer phase conductors. The field strength decreased to 1 kV/m at approximately 120 feet from the ROW center and to 300 V/m at approximately 300 feet from the ROW center. The maximum measured electric field strength beneath the 345 kV double circuit line was about 4 kV/m at the center of the ROW, and decreased to 1 kV/m and 100 V/m at distances of 69 and 160 feet from the ROW center, respectively.

Short circuit currents of 2 mA were measured from the EPA radiation analysis van and 0.6 mA from an intermediate sized automobile, when they were located in a position where the unperturbed field was about 9 kV/m. A 100 foot long, simulated wire fence produced a short circuit current of 0.9 mA to ground when aligned parallel to an outside conductor and subjected to a field strength of about 10 kV/m.

An average value of induced body current of about 13 μA/kV/m was determined for several individuals located in the electric field beneath the 765 kV line. For humans insulated from ground, the threshold for annoyance from transient spark discharge was about 6 kV/m. This is the maximum field strength at 3 feet above ground under the outer phase conductors of a 765 kV line with 60 feet of clearance (see Figure 1).

Based on this study we conclude that under normal conditions electric fields strengths under EHV overhead power transmission lines can be calculated with sufficient accuracy to preclude the necessity of field measurements. Exceptions might occur where the terrain is non-uniform or where geographical or man-made anomalies might significantly perturb the field. In addition it would appear that annoyance due to spark discharge is not likely to occur at distances greater than 100 feet from the center of the power line right-of-way, and then only for power lines that are 500 kV or greater.

INTRODUCTION

This report contains information on several physical parameters of environmental interest in the near vicinity of extra-high-voltage (EHV) overhead power transmission lines. The work consists of analytical analyses and subsequent field measurements for a number of different power line configurations. The study consisted of two phases: (a) an analytical evaluation of the electric field strengths in the vicinity of typical 345, 500, and 765 kV transmission lines, and (b) field measurements to determine actual field strength values under a 345 kV double circuit line and under 510 kV and 765 kV single circuit lines. The second phase included measurements of short circuit current (I_{sc}) to ground from several people, a car, a van, a farm tractor, and a simulated wire fence. Data were also obtained on transient spark discharge from people immersed in electric fields in an attempt to define thresholds for both perception and annoyance. This work was supported, in part, by the Nuclear Regulatory Commission through an interagency agreement, AT(49-24)-0125 [EPA-IAG-R5-0717].

Of particular interest for this study was the opportunity to make field measurements under a normally operating 765 kV line. An ideal measurement site was identified, with the assistance of the American Electric Power Company [1], near the Indiana and Michigan Electric Company's (I&M) Dumont Substation, approximately 20 miles south of South Bend, Indiana. I and M is a subsidiary of AEP. This particular location was chosen because of the flat terrain under the available transmission lines, the number of 765 kV lines available (four 765 kV lines enter the Dumont station and, in the event of an outage on one line, measurements could have been shifted to another 765 kV line), and the close proximity to the measurement site of the substation, ensuring that the operating voltage on the lines being used for the field measurements was accurately known. Field measurements were conducted during the period 12-14 May 1975.

ANALYTICAL EVALUATION OF FIELD STRENGTHS

A number of methods have been used to obtain theoretical values for the electric field strength beneath overhead transmission lines [2]. The method used to calculate electric field strengths in this report is one developed by Mr. John Walker of the Bonneville Power Administration, Portland, Oregon [3]. The procedure is implemented by a computer program which takes as input the electrical and geometric characteristics of the line. This data includes the height of the line conductors above ground, the number and geometry of the subconductors (if more than one is used) for each phase of the line, the line to neutral voltage on each conductor, the diameter of each subconductor, the phase spacing for the line, and the coordinates of the desired calculation point (i.e., the point at which one wishes to compute the field strength).

This calculation is based on the fundamental field equation

$$E = \frac{q}{2\pi\epsilon_0 r} \quad \text{where} \qquad (1)$$

E is field strength in volts/meter
q is charge per unit length in coulombs/meter
ϵ_0 is permittivity of air = 8.85×10^{-12} farads/meter
r is distance from the charge in meters.

When the geometry is the cross-section of interest is known, the only unknown in the above equation is q, the charge on the conductor. The charge can be calculated from

$$q = CV \quad \text{where} \qquad (2)$$

C is capacitance per unit length in farads/meter
V is voltage impressed on the conductor in volts.

The procedure incorporates the method of images where a set of equal and opposite charges are placed directly below the earth surface the same distance the conductors were above the earth. The cross-section of line charges now consists of charges representing the conductors and opposite charges on the conductor images in the earth to produce a line of zero potential at the earth's surface. The field strength due to the energized conductor can then be computed at any point. This program was modified to run on the IBM 370 computer available to EPA and was subsequently modified to determine values for the horizontal and vertical components of the field strength in addition to the total magnitude.

Several line types and configurations were analyzed with this program. Calculations were made for a number of line clearances and measurement heights for a 765 kV single circuit line and a 345 kV double circuit line, each with nominal physical specifications equal to the lines located at the measurement site and, in addition, for a 345 kV single circuit line and a 500 kV single circuit line. Typical line specifications were obtained from AEP and the EHV Transmission Line Reference Book [4]. Table 1 summarizes the particular line configurations chosen for this study which are assumed to be representative of possible configurations found at various locations in the United States. The transmission line, which is suspended between two towers, hangs in a catenary curve so that the height above ground varies from a maximum at the towers to a minimum somewhere between the towers. For simplicity line height will be expressed as the minimum vertical distance between the ground surface and the line. Typical tower heights range from approximately 50 to 100 feet.

Table 1

Specifications for Transmission Lines Used in Measurements

Nominal Specifications	345 kV DBL	345 kV Single	500 kV Single	765 kV Single
Phase Spacing (ft.)	33.5	45	35	44
No. of Subconductors	3	3	3	4
Diameter of Subconductors (in.)	1.165	1.108	1.621	1.165
Spacing of Subconductors (in.)	18	18	18	18

The computed values of the magnitude of the electric field strength, E, are plotted vs. the distance from the center of the line right-of-way (ROW) for the 765 kV line configuration in Figure 1. This graphical display shows only half of the total lateral profile of the electric field strength since the field is symmetrical about the center of the ROW. Figure 1 shows the magnitude of the field strength at a distance of 3 feet above ground for line clearances of 30, 40, 50, 60, and 70 feet respectively. Actual line installations always exceed 40 feet in this country, 40 feet being the minimum design clearance used for 765 kV technology. The family of curves is intended to illustrate the effect of line clearance on the value of the field strength beneath the line. Peak values are seen to vary from 17.8 kV/m to 4.8 kV/m for line clearances varying from 30 feet to 70 feet respectively. In all cases of line clearance, the field strength is down to about 1 kV/m at a distance of approximately 170 feet from the center of the ROW. From this point the field diminishes very slowly until it reaches a value of 100 V/m at a horizontal distance of 330 feet. Commonly found minimum clearances for presently operating 765 kV lines in this country cover the range of 40 to 60 feet which implies an unperturbed maximum, field strength range of 11.8 to 6.3 kV/m.

Figure 2 is a plot of the variation in the electric field strength at various heights above ground for line clearances of 30, 40, 50, 60, and 70 feet for the same 765 kV line. It is evident that the change in field strength over moderate changes in heights above ground is small. This holds true until the height above ground begins to approach the line clearance. As an example, for a line clearance of 40 feet, the field strength changes less than 20 percent for all heights from ground level to 14 feet above ground. This slight variation with height above ground will be evident in some of the experimental data presented later. As the line height above ground increases, its influence on the field strength near the ground decreases, where, for example in the 70 foot clearance case, the change in field strength is less than 11 percent for the same 14 foot variation in height above ground.

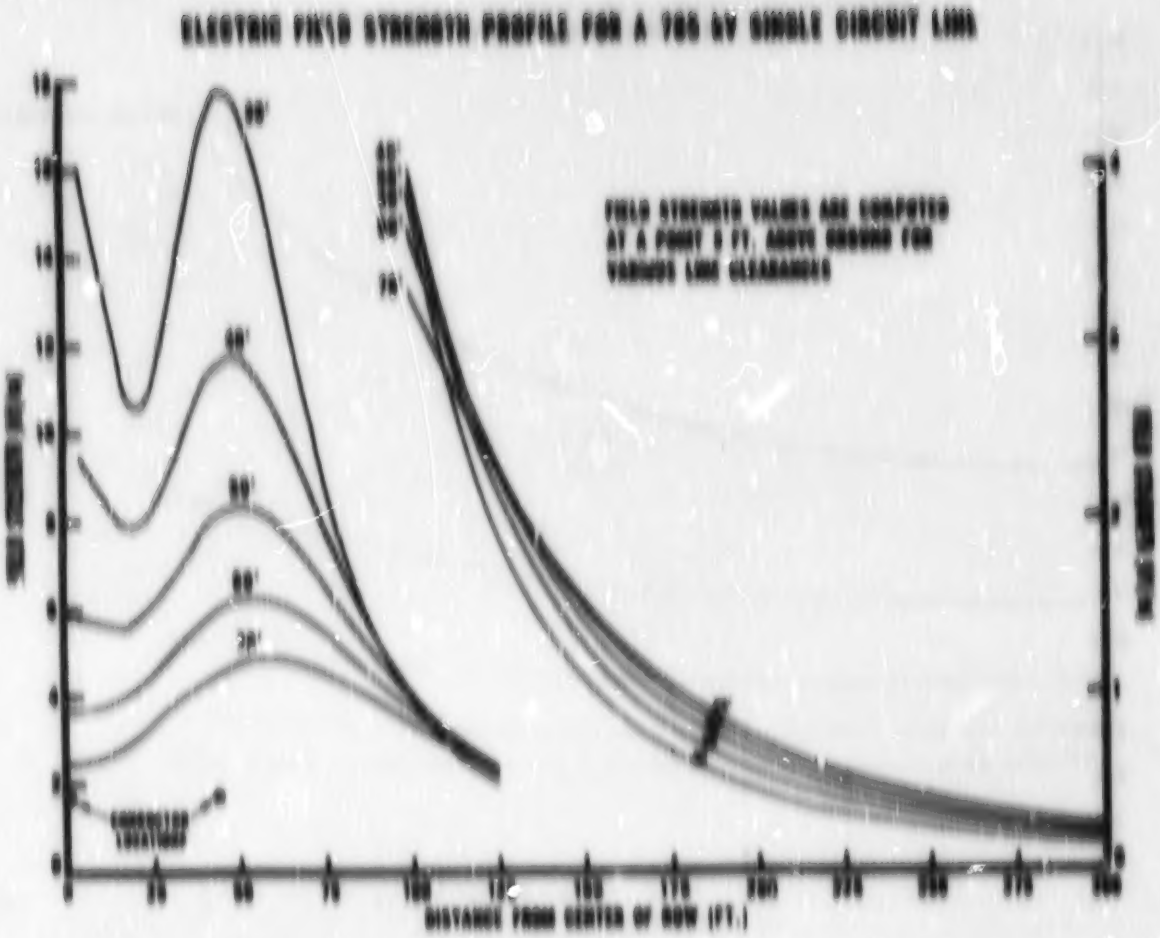
ELECTRIC FIELD STRENGTH PROFILE FOR A 765 kV SINGLE CIRCUIT LINE
FIELD STRENGTH VALUES ARE COMPUTED AT A POINT 3 FT. ABOVE GROUND FOR VARIOUS LINE CLEARANCES
DISTANCE FROM CENTER OF ROW (FT.)

Figure 1 Electric field strength profile for 765 kV line. (Here two ordinate scales are used, the left for distances to 125 ft., the right for distances greater than 125 ft.)

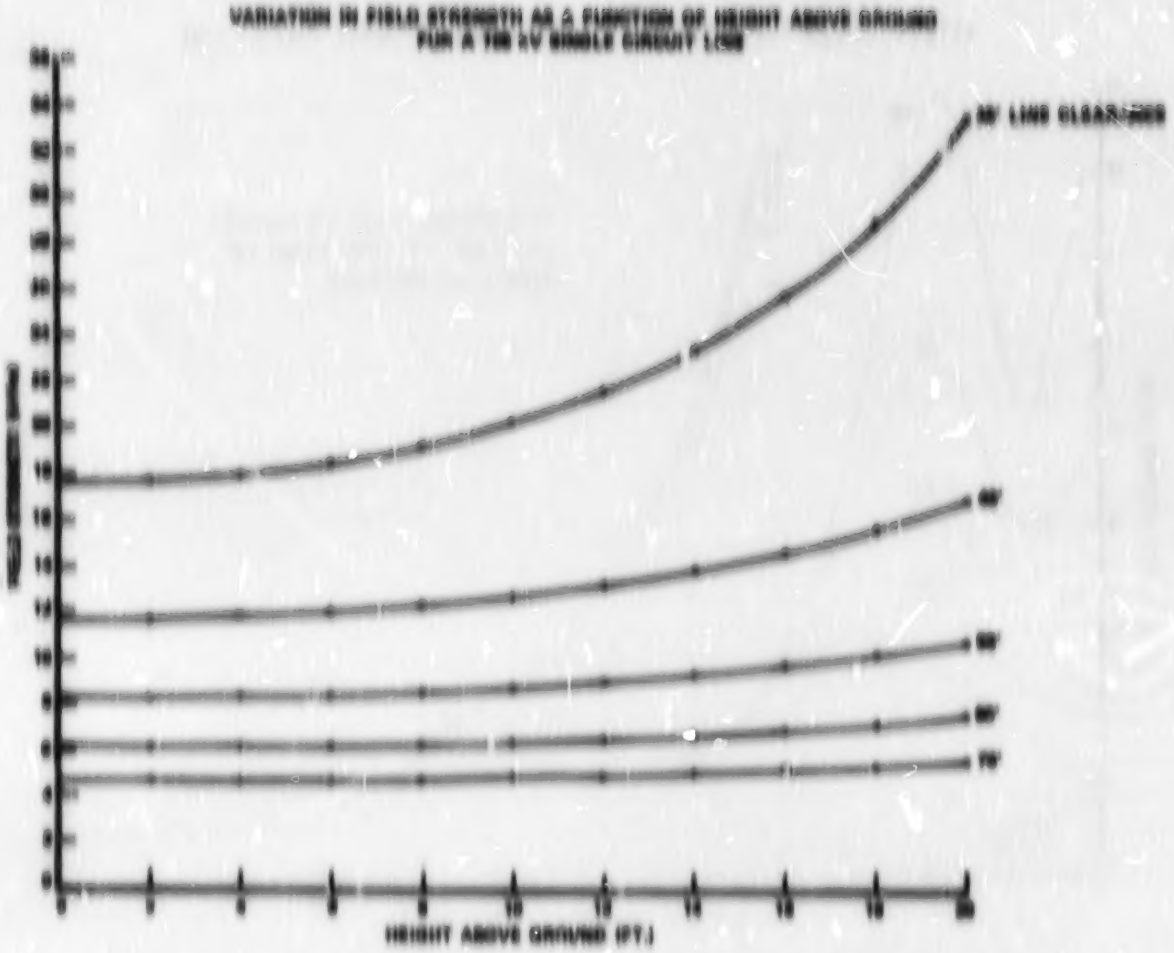

Figure 3 Variation in field strength as a function of height above ground for a 765 kV line

Similar field strength plots are provided in Figure 3 and 4 for a 500 kV line. Maximum gradients vary from 5.9 kV/m at a clearance of 30 feet to 4.3 kV/m with a 50 foot clearance. Here the gradient is down to 1 kV/m at about 115 feet from the ROW center and 100 V/m at 330 feet. Again the variation of gradient with height above ground is not rapid, as long as the line has sufficient clearance.

Figures 5 and 6 contain similar information for a 345 kV double circuit line. Here the low line clearance of only 30 feet produces a well defined peak in the vicinity of the conductors. Again the variation of electric field strength with height above ground, in cases of realistic clearances, is slight. The maximum field strength lies in a range of 11.1 to 4.0 kV/m for clearances from 30 to 50 feet respectively. The field strength is down to 1 kV/m at approximately 80 feet from the ROW center and 100 V/m at 330 feet.

Data for a single circuit 345 kV line are given in Figure 7 and 8. It was noted [4] that a number of lines of this type have minimum clearances in the neighborhood of 35 feet. Such a clearance would imply a field gradient of 7.8 kV/m under the conductor at 3 feet above ground. This is comparable to the field strength produced at the same height above ground under a [illegible] kV line with a nominal clearances of 35 feet (interpolated from Figure 1). The maximum gradient values range from 11.1 to 5.6 kV/m for the 345 kV single circuit line with corresponding clearances ranging from 30 to 40 feet. The field strength is down to 1 kV/m at approximately 80 feet from the ROW center and down to 100 V/m at approximately 150 feet.

From reference 4 minimum clearances for 345, 500, and 765 kV lines were identified and corresponding calculated electric field strength values are summarized in Table 2. It is noted that the field strengths associated with 345 kV lines can approach those found near 765 kV lines.

Additionally, it appears that the unperturbed electric field strength does not vary appreciably over the average height of a man standing on earth, or about 6 feet. In the case of a 765 kV line with a 40 foot clearance, this variation amounts to about 3-4 percent maximum. It should be noted that this is with respect to the unperturbed electric field before the individual is introduced into the field. Perturbations caused by the conductive character of humans can cause relatively large increases in the immediate surface gradient by concentrating the field [5].

In all of the above graphs, the electric field strength has been specified in terms of the resultant field strength or its magnitude. In another calculation, the vertical and horizontal components of the electric field were determined. Figures 9 and 10 show how these components vary at two different heights above ground for a 765 kV line with a clearance of 40 feet. The interesting aspect to these plots is the increase in the absolute value of the horizontal component as the height above ground increases. As the height approaches the line, the influence of the adjacent horizontally spaced phases becomes significant, causing the horizontal component of the gradient to be a substantial fraction of the magnitude. However at heights above ground of less than 6 feet, the horizontal component is essentially negligible.

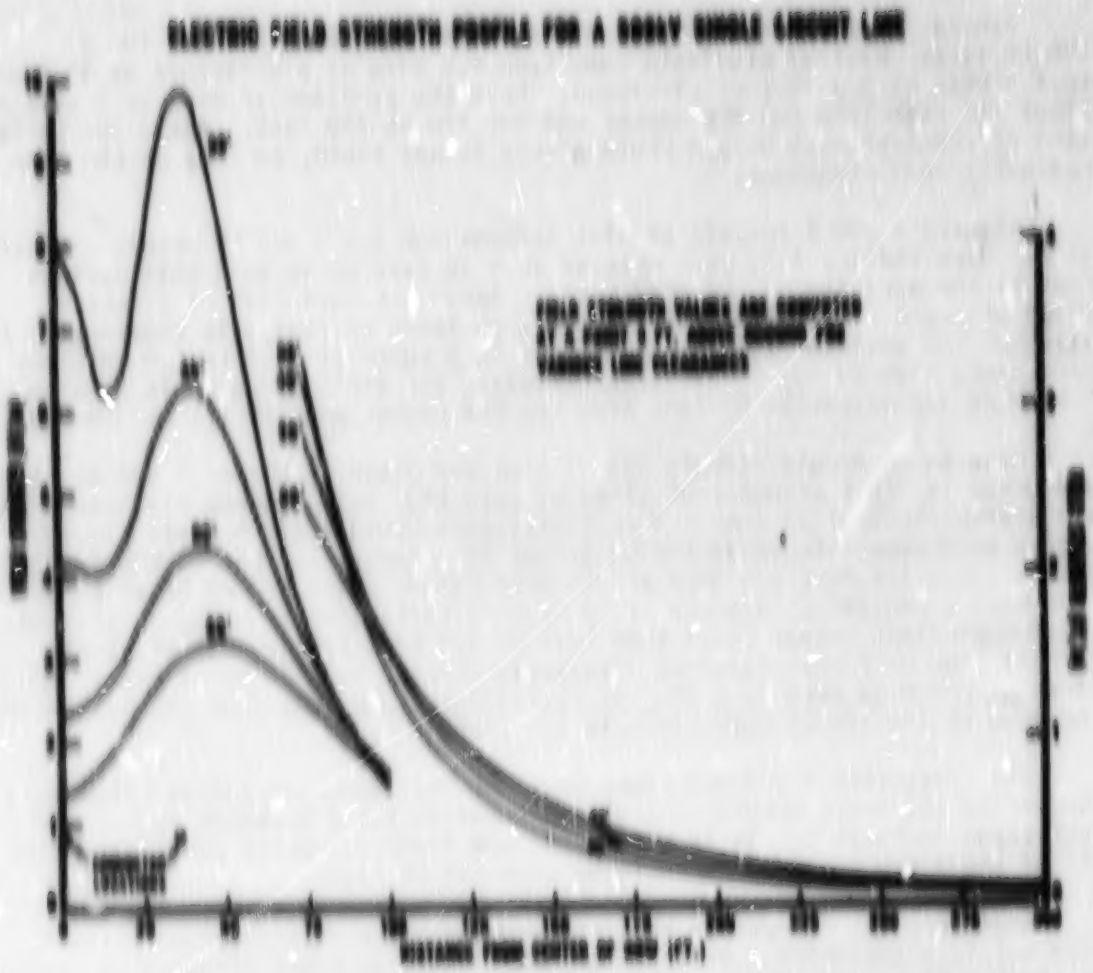

Figure 3 Electric field strength profile for 500 kV single circuit line (Here the profile is used to the left for distances less than 100 ft., the right for distances greater than 100 ft.)

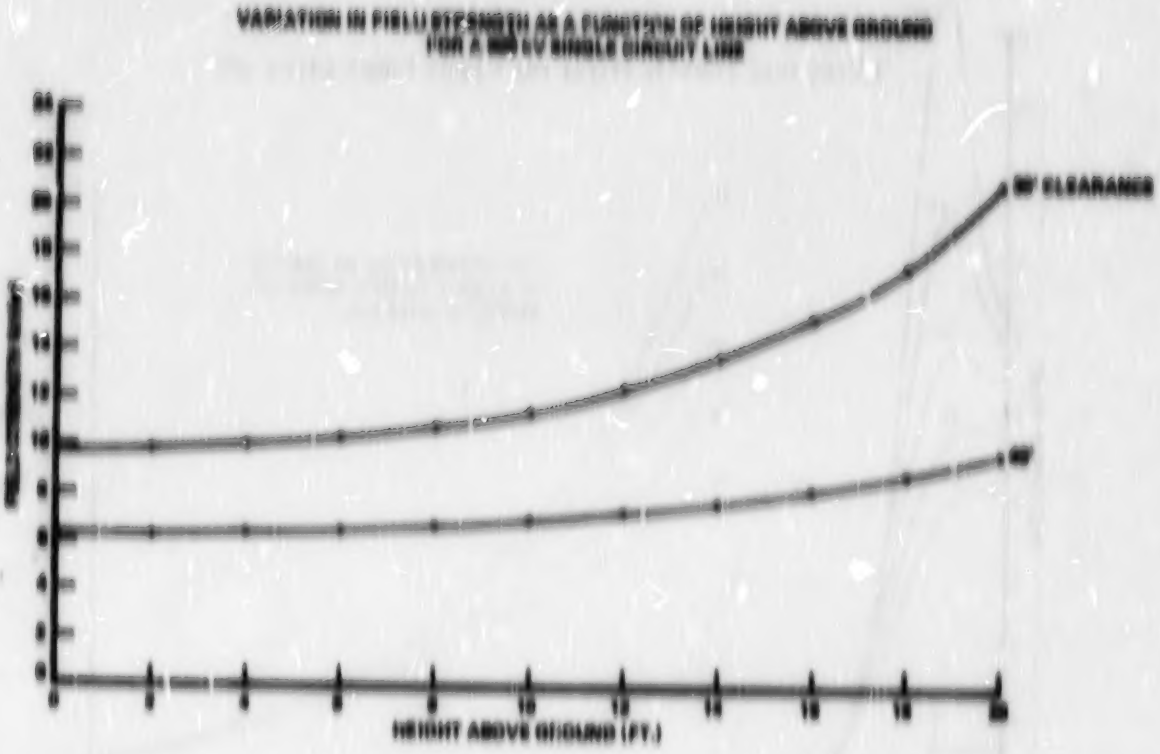
VARIATION IN FIELD STRENGTH AS A FUNCTION OF HEIGHT ABOVE GROUND
FOR A 500 KV SINGLE CIRCUIT LINE
80' CLEARANCE
HEIGHT ABOVE GROUND (FT.)

Figure 4 Variation in field strength as a function of height above ground for a 500 kV single circuit line

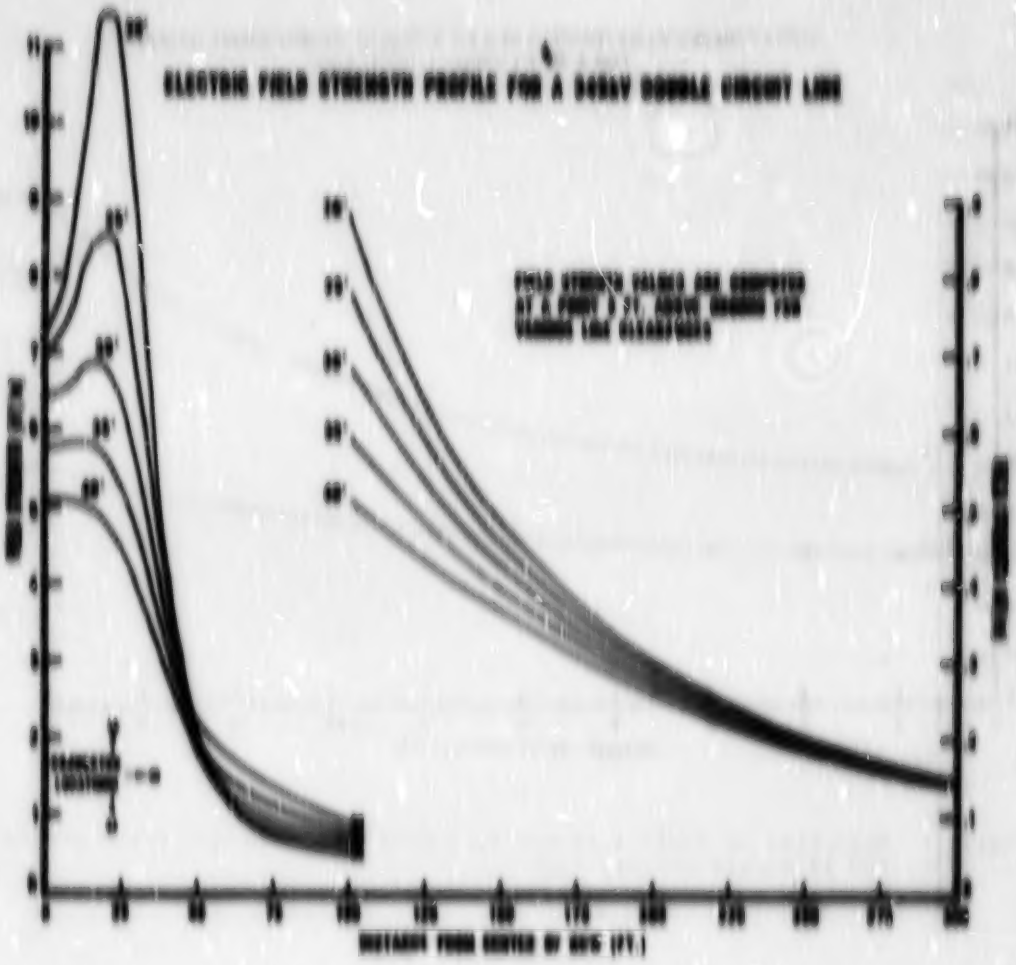

Figure 5 Electric field strength profile for 345 kV double circuit line (Note that two ordinate scales are used, the left for distances less than 100 ft.; the right for distances greater than 100 ft.)

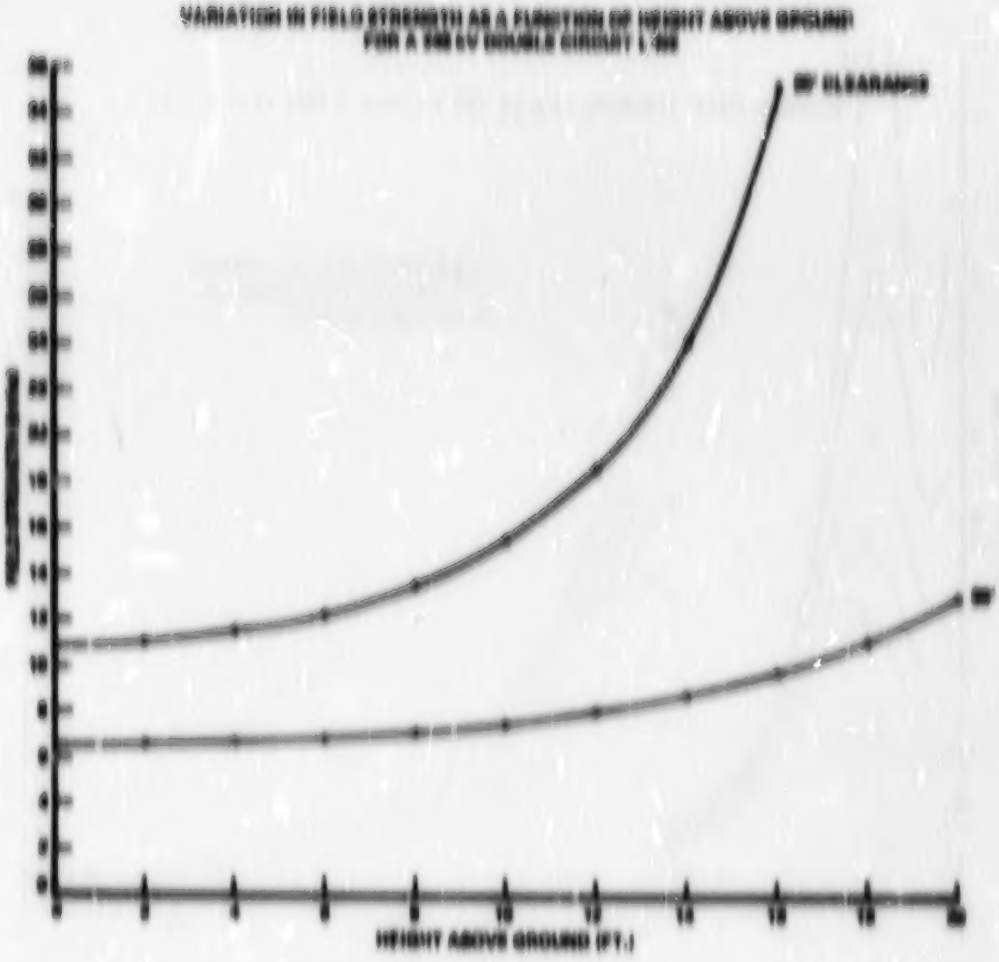
VARIATION IN FIELD STRENGTH AS A FUNCTION OF HEIGHT ABOVE GROUND
FOR A 345 KV DOUBLE CIRCUIT L-345
80' CLEARANCE
HEIGHT ABOVE GROUND (FT.)

Figure 6 Variation in field strength as a function of height above ground for a 345 kv double circuit line

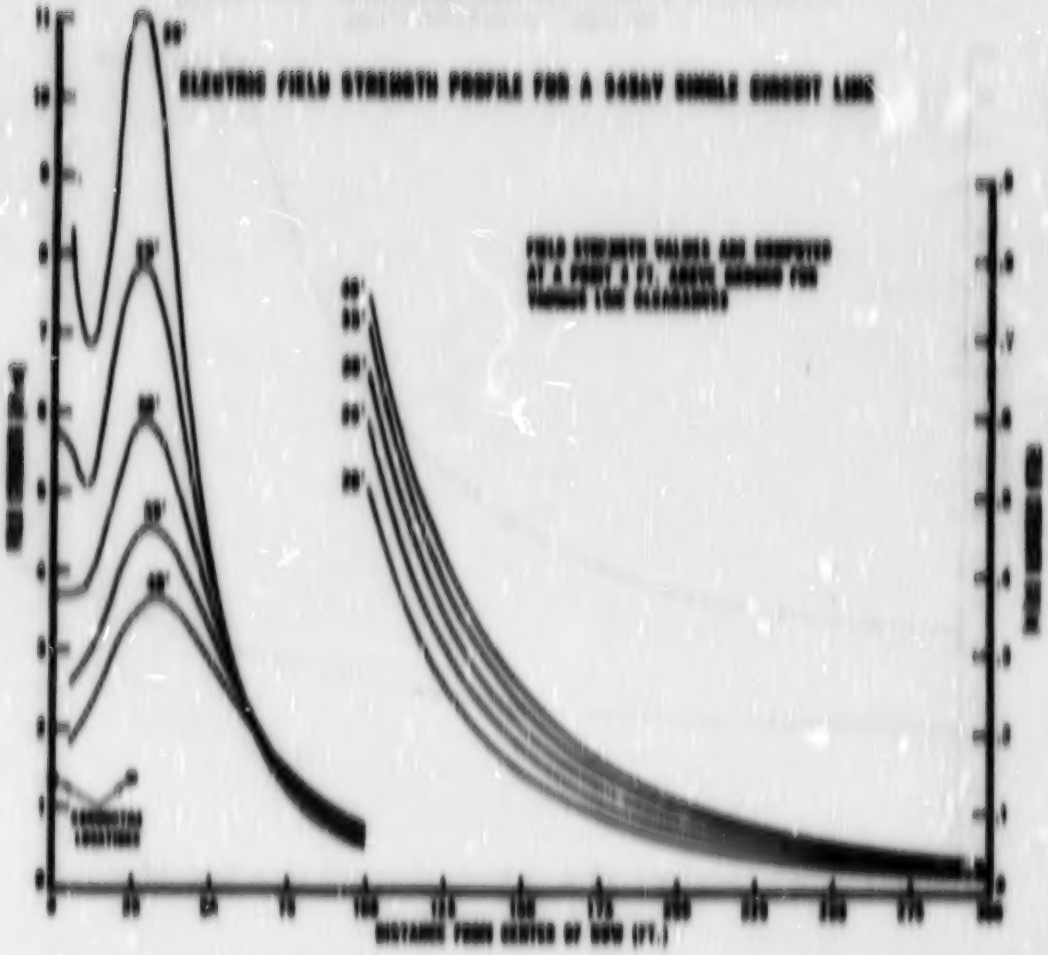

Figure 7 Electric field strength profile for 345 kV single circuit line. (Note that two ordinate scales are used, the left for distances less than 100 ft., the right for distances greater than 100 ft.)

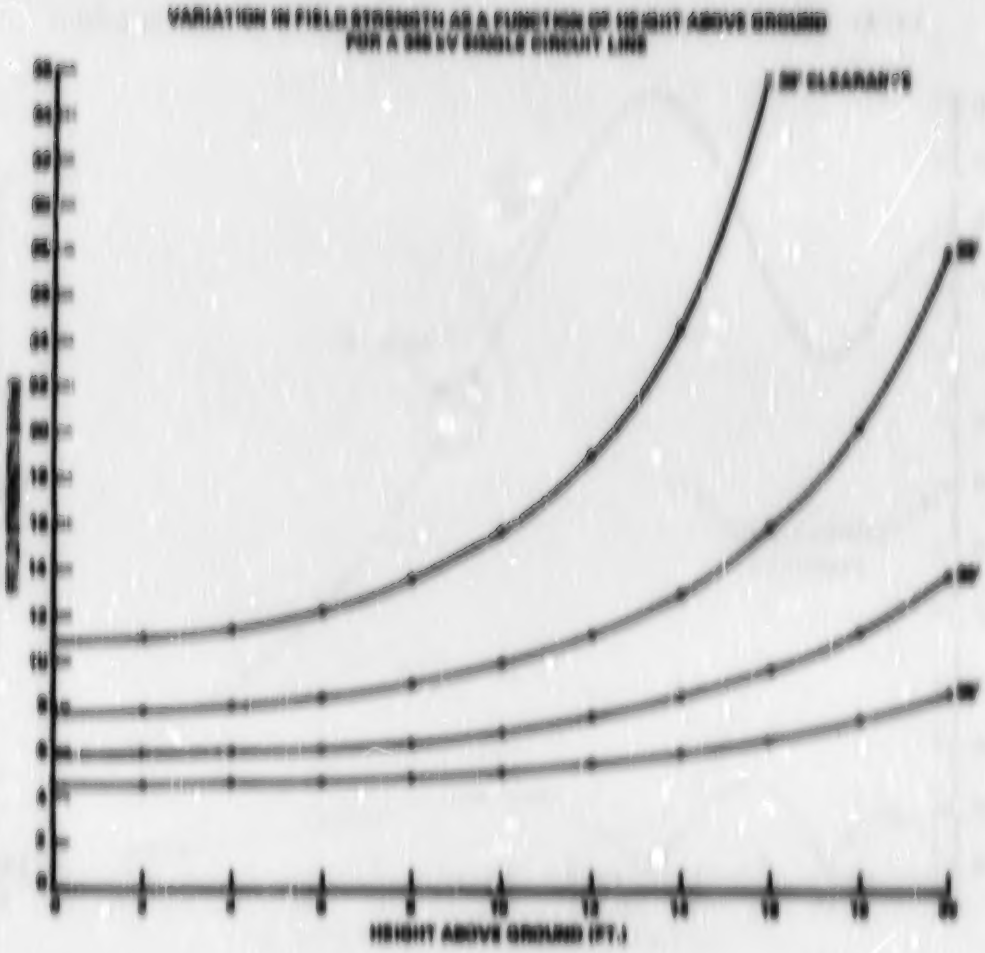

Figure 8 Variation in field strength as a function of height above ground for a 345 kv single circuit line

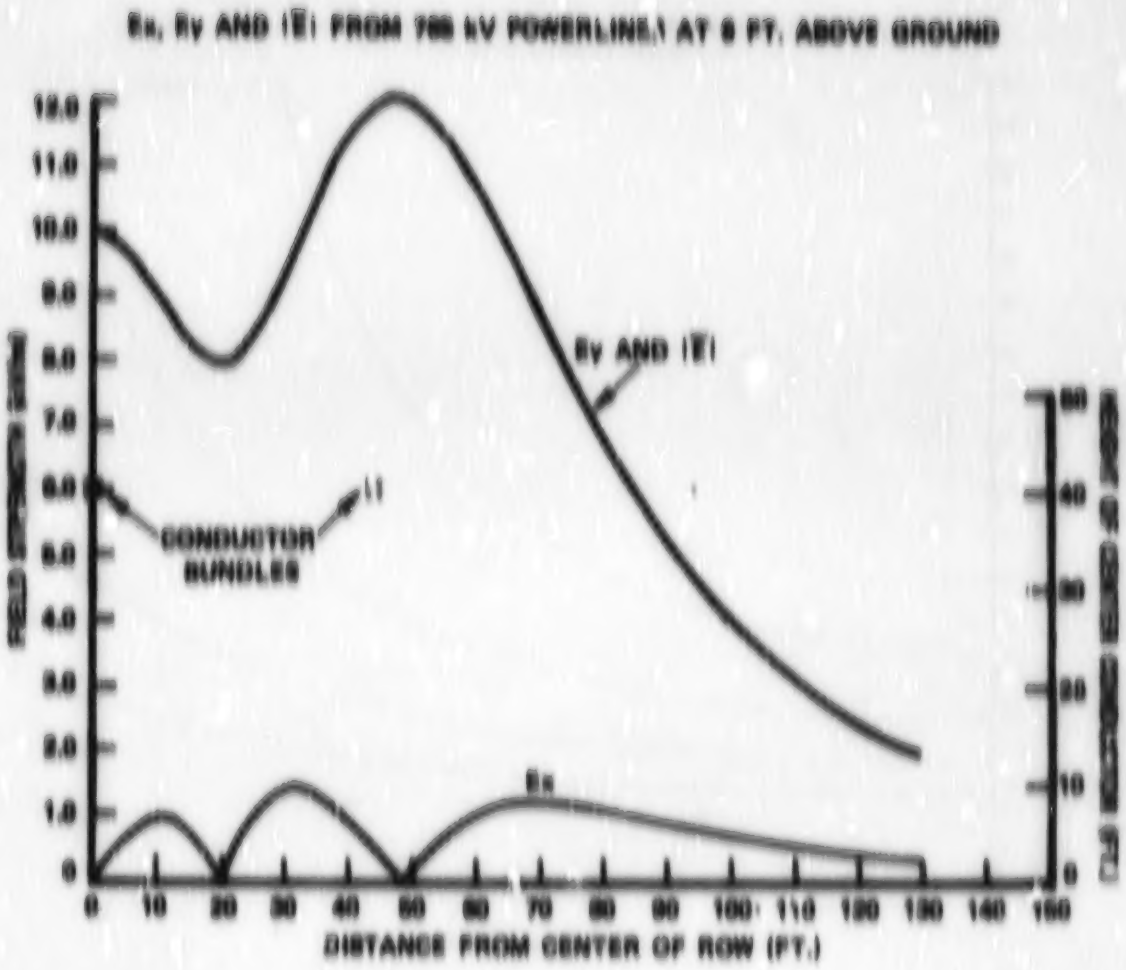

Figure 9 Bx, By, and |E| from 765 kV power lines at 6 ft. above ground

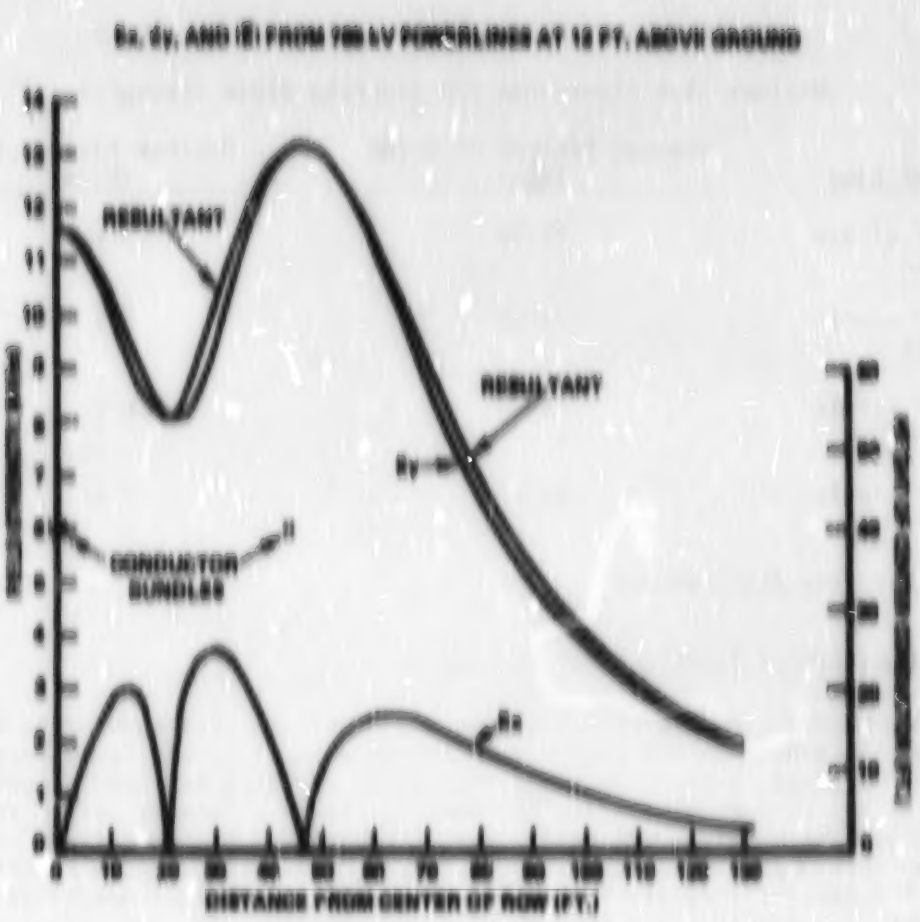

Figure 10 Ex, Ey, and |E| from 765 kV power lines at 10 ft. above ground

Table 3

Minimum Line Clearances and Expected Field Strengths

Type of Line	Typical Minimum Clearance (ft.)	Maximum Field Strength[a] (kV/m)
345 kV single circuit	35-45	4.5-8
345 kV double circuit	30-40	5-7
500 kV single circuit	40	6-7
765 kV single circuit	40-50	8-12

[a]At three feet above ground.

FIELD MEASUREMENT TECHNIQUE AND RESULTS

Measurements of electric field strength were accomplished using a Monroe Electronics model 284 A-1 portable differential AC electric field meter. This meter is a small, battery operated instrument designed for use in general physical and biological testing for electric field intensity levels in the vicinity of high voltage AC transmission equipment. Plates attached to the top and bottom of the instrument constitute the sensing electrodes with the axis of sensitivity normal to the plates. A four foot long handle is used to reduce field distortion created by the presence of the individual performing the measurement. Table 3 provides a summary of the more pertinent specifications for the instrument.

The sensitive electrodes consist of two parallel plane conductors separated by the metal instrument case. These electrodes are exposed to the AC field to be measured and are oriented with their plane perpendicular to the desired incident AC electric field component. These electrodes are connected to the inputs of a differential preamplifier. The preamplifier output is a voltage proportional to the RMS value of the differential AC electric field incident upon the sensitive electrodes, and is independent of the frequency of the incident AC field.

The calibration of this meter is based on the "square meter panel" method of measuring AC electric field strength at ground level below an extra high voltage transmission line. The "square meter panel" is a one square meter metallic panel surrounded by and insulated from a guard ring. The center panel is slightly less than one square meter, since fringing in

Table 3

Specifications of Monroe Electronics Model 235A-1
Portable Differential AC Electric Fieldmeter

Range: Full scale meter ranges of 5, 10, and 55 kV/m

Accuracy: ±5% of full scale

Minimum Detectability: ~100 V/m

Frequency Response: Independent of frequency for normal power transmission frequencies (50 Hz to 1,000 Hz)

Stability: Instability as a function of time, temperature, and battery voltage is included in the overall accuracy specification

Battery: Type - Standard 9 volt transistor radio battery (Eveready No. 216 or equivalent) - one required

Life - 100 hours minimum

Physical Dimensions: 4 1/4" deep x 6 1/2" wide x 5 3/4" high not including handle

Readout: Analog meter movement

the air gap divides the displacement flux equally, making the effective area of the center panel equivalent to the center of the gap which encloses one square meter. The guard ring extends one half meter beyond the center panel. Virtual electric ground should be less than 10 cm below the square meter panel. The panel is then positioned below an extra high voltage (300-500 kV) single phase transmission line at least 30 feet above ground and connected to the true earth through a microammeter. The guard ring is connected directly to true earth ground. The magnitude of the 60 Hz phasor RMS voltage gradient is obtained by

$$\bar{E} = 0.3I(kV/m)$$ where I is measured in microamperes.

The meter is then positioned directly over but not touching the center panel. When making measurements under power lines, the operator should be at least one meter away from the field meter.

A model M100 optical tapemeasure rangefinder, manufactured by Ranging, Inc., was used to optically determine the various line heights at the time of measurement in the field. This particular instrument covers the range of

6 to 150 feet. Due to a measurement error of several percent, all distances determined with this device were measured 10 times. The mean value of these 10 readings was then checked for accuracy by setting the range finder to this mean value and measuring the actual distance. A typical error of ±3 percent was determined for the instrument.

The procedure for determining the field strength lateral profile was to establish a point on the line which was taken as the origin of a coordinate system from which measurements were taken along a perpendicular direction to the transmission line. A surveyors transit was utilized to assist in these mappings and determining the point of minimum sag for each line. For each power line measured, the lateral profile was determined as nearly as possible along a line perpendicular to the powerline at the point of minimum sag. This was done since (a) it was of interest to determine the maximum field strengths possible, and (b) it was presumed that the results obtained would more nearly equal the calculated values of electric field strength since the computer model assumes the transmission lines to be infinite in extent and perfectly horizontal. In reality, the line hangs as a catenary between adjacent towers. After staking out the profile line, a 100 foot nonmetallic tape measure was used to measure lateral distance and measurements of vertical and horizontal field gradients were taken every three feet from the ROW center. When the field strength reached approximately 1 kV/m, readings were taken at 10 foot intervals. Figure 11 presents a sketch showing the geometric layout and phasing of the 765 kV Marysville line and the 345 kV Twinbranch line used for field measurements. A picture of the measurement process is seen in Figure 12. The ground surface condition under the 765 kV line (see Figure 12) was freshly disced soil, while the ground under the 345 kV line had grass cover and was fairly hard. The soil was a clay which becomes very hard when dry and very sticky when wet.

Figure 14 shows the results of the field measurements taken under the 765 kV Marysville line near the Dumont Substation. Measured data are plotted as discrete points while the calculated values of field strength are shown by the solid curve. Substation personnel provided accurate voltage measurements for the time of the measurements. This data and the measured line clearances, given in Table 6, were used as input data to the computer program to compute a theoretical value for the gradient. Specific phase to neutral voltages were used in the program and account partially for the lower gradient observed under the phase 1 side of the ROW. Additionally the phase 1 bundle was slightly lower than the other outside phase by 0.6 foot. Maximum discrepancy between theoretical and measured values of field strength was about 8 percent, this occurring on the phase 1 side of the line.

Measured values of field strength (vertical component) had a maximum value of 9.9 kV/m approximately 10 feet beyond the outer most conductor of phase 1. The measured field was down to 1 kV/m at 170 feet from the ROW center and down to 100 V/m at 360 feet on the phase 3 side of the ROW. The field was down to 1 kV/m and 100 V/m at 170 and 335 feet respectively on the phase 1 side of the ROW.

PHASE CONFIGURATION OF 765 kV MARYSVILLE LINE

(NOT TO SCALE)

PHASE CONFIGURATION OF 345 kV TWIN BRANCH LINE

Figure 11 Phase configuration of 765 and 345 kV lines used for measurements

Figure 13 Photograph of field measurements technique

Figure 13 Photograph of 765 kV line measurement site

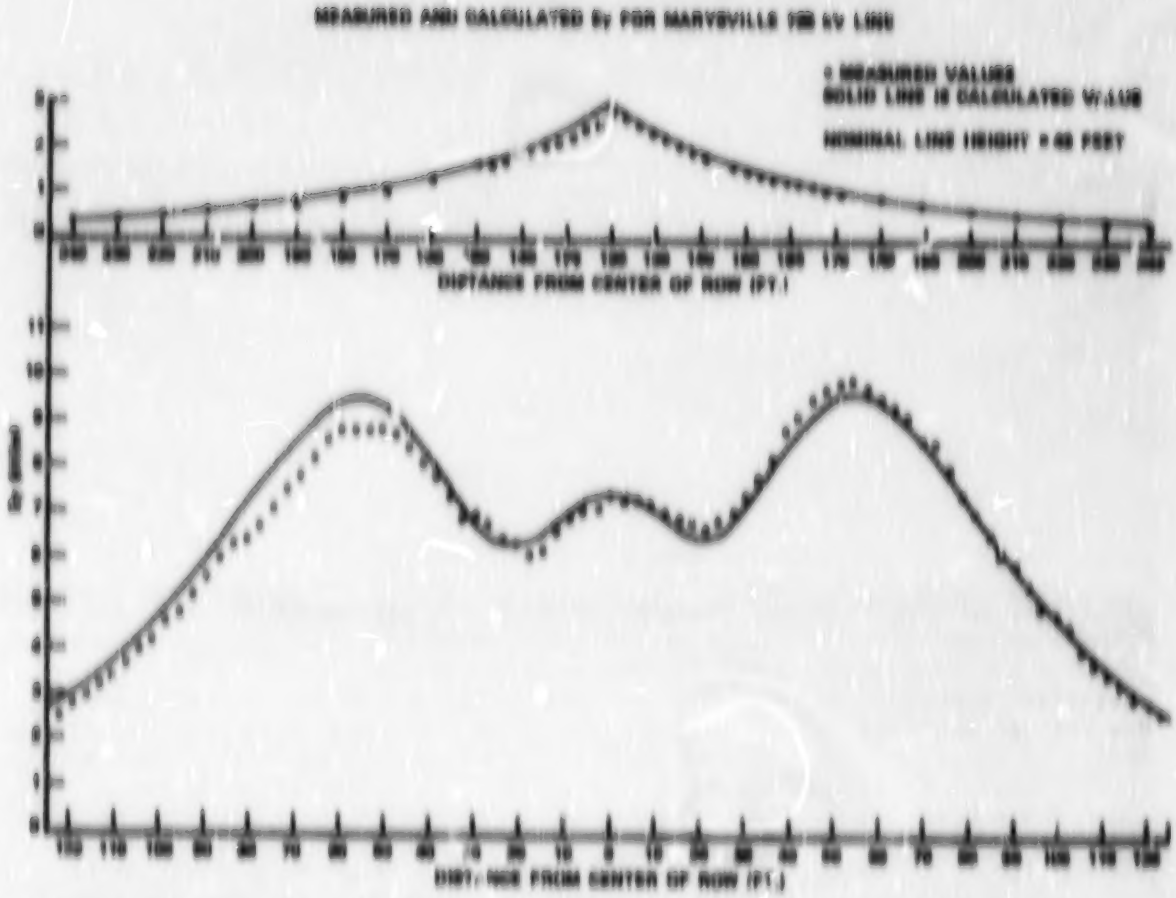

Figure 14 Measured and calculated By for Marysville 765 kV line. (Note upper curve gives values for field strength beginning at 150 ft.; the lower from the center line to 150 ft.)

Table 4

765 kV Marysville Line Measured Clearances and Voltages

	Phase to Neutral Voltage (kV)	Clearance (feet)*
Phase 1	443.125	48.9
Phase 2	438.750	46.9
Phase 3	445.000	48.3

Average Phase to Phase Voltage = 766.1

*Height above ground to center of each phase bundle.

As a check on the computer program, field strength measurements were conducted at three different positions longitudinally along the 765 kV line where the line clearances were significantly different. Subsequently the theoretical values were obtained and compared with the measured values. Readings were taken directly beneath the phase 3 bundle without regard to finding the absolute peak value of the field strength. This data is presented in Table 5. These comparisons give a feel for the validity of using the analytical approach at locations other than the point of minimum line height. New voltage readings were again taken at the time of these measurements and incorporated in the analytical solutions. The results show that as the line becomes more inclined with respect to the ground more discrepancy occurs between measured and calculated values. The theoretical approach assumes that the line conductors are horizontal and infinite in extent. However, at points along a transmission line where the line sag is essentially symmetric about the measurement point, the correlation between measured and calculated electric field values is excellent.

An attempt was made to measure the horizontal component of the electric field along the lateral profile and compare this data with the calculated results. In general the agreement between the two methods was not as good as expected; there appeared to be an anomaly in the results. A maximum horizontal component of 1.2 kV/m was measured at approximately 18 feet from the center of the ROW. This value is twice as large as the calculated value and occurs at a point where the theory says a null would appear. There appeared to be another broad peak in the neighborhood of 80 feet from the ROW center of about 0.8 kV/m. This value is also about a factor of two above the theoretical value but occurs generally in the correct area spatially. It is not clear why the two methods diverged in this case but possibilities include: (a) a calibration phenomena with the field meter in terms of its orientation with respect to the ground and (b) the possibility of inaccurately holding the field meter in a horizontal position. An error in orientation of approximately 5° from true horizontal would be responsible for a possible

Table 5

Measured and Calculated Field Strength
at Several Line Heights
765 kV Marysville Line

Position	Line Height (ft)*	Field Strength (kV/m) Measured**	Calculated
1	47.5	9.5	9.4
2	51.3	7.5	8.1
3	71.3	3.9	4.6

*Center phase.
**Values measured under outside phase.

contribution of about 10 percent from the vertical component and thus could affect the horizontal readings enough to cause the above effect. A more careful investigation of the horizontal component of field strength is warranted to fully document this apparent discrepancy. At measurement heights less than 6 feet above ground, the horizontal component does not significantly contribute to the resultant field strength.

Measurements were made of the field strength at various heights above ground up to a maximum height of 8 feet. This data is presented in Table 6 and confirms the rather slow increase in field strength as the measurement height is increased. Data was taken at a lateral point relative to the minimum line height of the 765 kV line where the field was a maximum at 3 feet above ground. Maximum variation was about 30 percent and probably reflects the distortion of the local field by the observer as he bent down for lower readings and reached upward for the highest readings.

A field strength profile for the 345 kV Twin Branch double circuit line was taken using a similar approach. Figure 15 shows the spatial dependence of the electric field with distance from the center of the ROW. A fence running parallel to this line prevented measurements at extended distances on one side. The data is plotted from 40 feet on one side to 220 feet on the other. Maximum field strength at 3 feet above ground was observed to be 4.1 kV/m at the center of the ROW. The field strength values decreased to 1 kV/m and 100 V/m at distances of 69 and 160 feet respectively. Theoretical values of the field strength are plotted as a solid curve to show the comparison of the methods, which is quite good, being typically within 4 percent. Table 7 gives the measured phase to neutral voltages on this line and the clearances of the various phases used in the computer program. Only the height to the lowest phase was actually measured; other line heights were assumed by adding the phase spacings given in Figure 11 to this lowest line height.

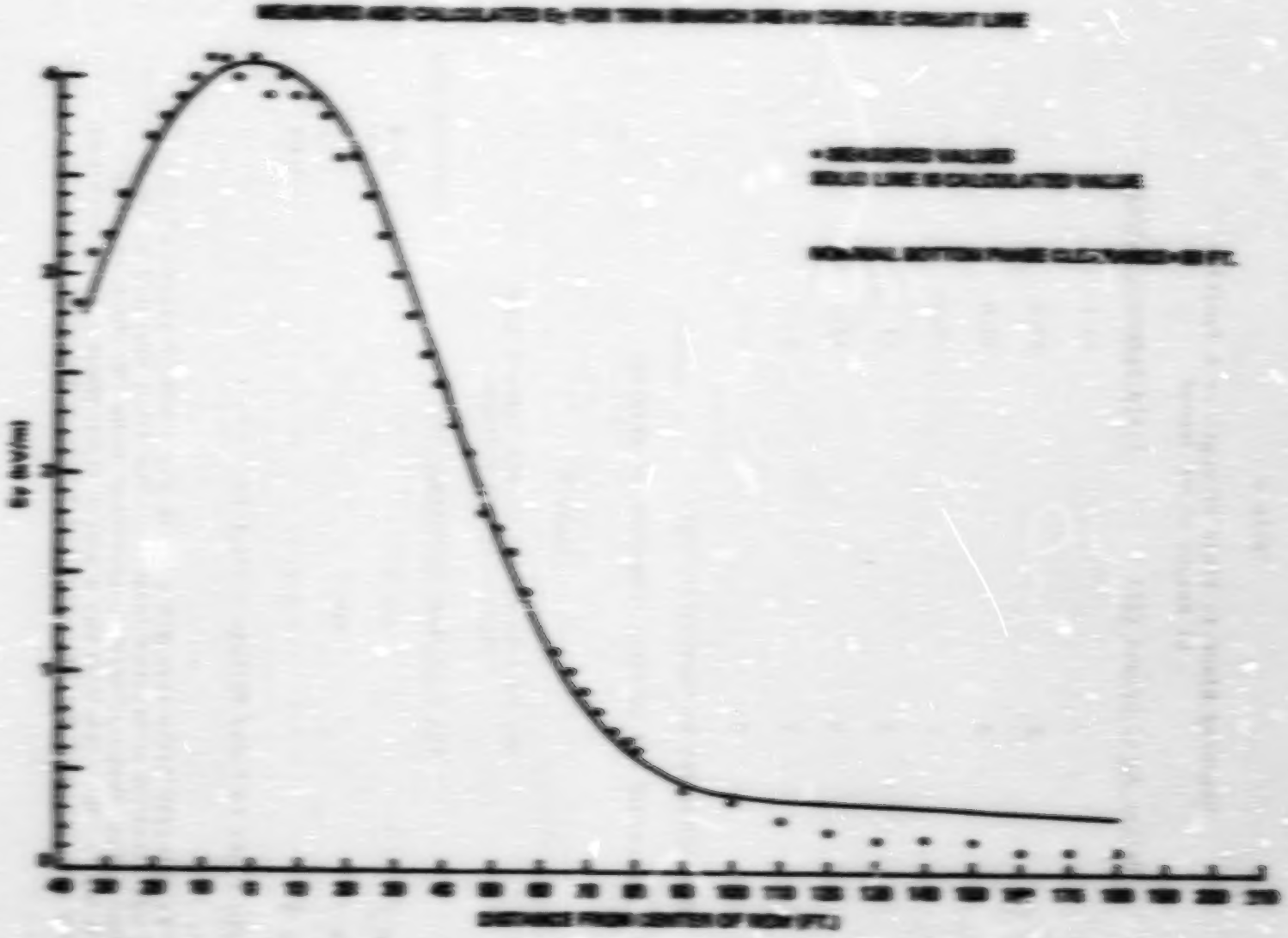

Figure 15 Measured and calculated By for Trois Branch 345 kV double circuit line, at 3 ft. above ground.

Table 6

Measured Electric Field Strength as a Function of Height Above Ground

Height Above Ground (ft)	Field Strength (kV/m)*
1	10.1
2	10.4
3	10.0
4	10.1
5	11.0
6	12.5
7	13.0
8	13.0

Data taken under 765 kV Maryuvilla Line.

*Value determined for vertical component of gradient.

Table 7

345 kV Twin Branch Double Circuit Line Clearances and Voltages

	Phase to Neutral Voltage (kV)	Clearance (ft)
Phase 1	205.5	50.4
Phase 2	206.1	71.9
Phase 3	206.1	95.4

Average Phase to Phase Voltage = 356.6 kV.

An electric field strength profile for a 500 kV single circuit line was obtained at another location. The line, operated by the Potomac Edison Company, extends east from Doubs, MD which is south of Frederick, MD. The line was a single three-phase circuit with each bundle consisting of two conductors of 1.8 inch diameter, spaced

18 inches apart and oriented horizontally, each bundle being spaced 35 feet apart. Two shield wires spaced 54 feet apart were located at a height of 73.8 feet. The voltage on the line at the time of the measurements, November 2, 1974, was 510 kV according to substation logs. The right-of-way was 200 feet wide, 100 feet on either side of the center line, at the measurement site.

Measurements were made with the Monroe meter over nearly flat terrain essentially as described above and the vertical line heights were determined with an optical range finder. Figure 16 presents the measured data as points and the analytical values as a solid curve. The maximum variation between measured and computed values is of the order of 5 percent.

MEASUREMENTS OF SHORT CIRCUIT CURRENT AND PERCEPTION

Short circuit currents to ground (I_{sc}) were determined using two different vehicles immersed in a fairly intense field. A 1973 Chevrolet Malibu (intermediate sized) was driven to a point under one of the outer conductors of the 765 kV Marysville line where the field strength at three feet above ground, when the vehicle was not present, was about 9 kV/m (see Figure 17). When the car was present under the line, the converged electric field was observed to be 16-17 kV/m depending on position when the meter was placed approximately 12 inches above the roof. Measurements inside the vehicle showed essentially a zero gradient except very near the windshield. Current measurements were made with the vehicle situated directly on the earth and when driven onto a set of hot-line blankets to insure good insulation of the car from ground. I_{sc} was measured as 80 μA when the vehicle was in contact with the earth and 620 μA when insulated from earth by the blankets. A copper ground rod was driven into the earth to provide a good ground connection for the current measurement. A Triplet model 601 Type 3 solid state VOM was used to measure the current.

The large EPA electromagnetic radiation analysis van (see Figure 18), a 27 foot fiberglass body vehicle with steel ribbing, was similarly tested in the normally ambient 9 kV/m field. Electric fields of 35 kV/m could be found by carrying the survey meter up the rear ladder of the van and holding it a foot above the van roof (Figure 19). The height of the van roof is about 10 feet above ground. With the van in normal contact with the earth, I_{sc} was 2.0 mA and when driven onto the hot-line blankets did not noticeably change, indicating that the van tires are very good insulators as opposed to the tires on the automobile.

The transient spark discharge was very uncomfortable when an observer standing on the ground touched the van chassis. Table 8 gives values of body currents while different individuals stood on a hot-line blanket and shorted the van to ground through themselves to the ground rod. In this situation the initial transient discharge effect was quite startling and the continual current flow thereafter was very uncomfortable. A typical value of 1.6 mA was observed. A 15 kΩ resistor was used to short the van to ground and a

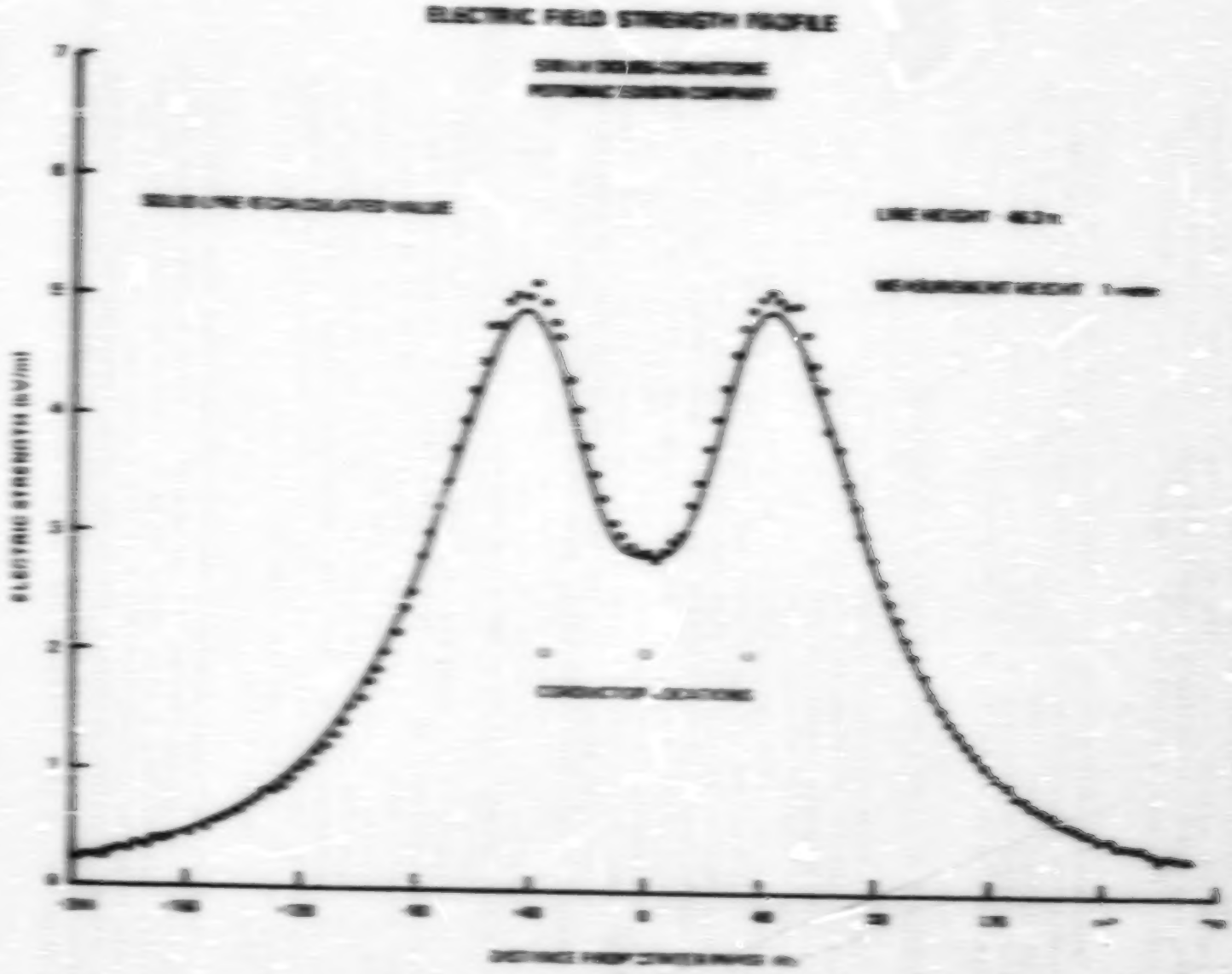

Figure 26 Measured and calculated By for Double-Conductor 500 kV single circuit line

Figure 17 Measurement of f_{gu} for Chevrolet car

Figure 18 Measurement of I_{xx} for RPA van

Figure 18 Measurement of electric field above roof of van

Table 8

Body Currents While Shorting Van to Ground

Subject	Body Current mA
A	1.6
B	1.6
C	1.4
D	1.6

current of 1.6 mA was observed as compared to 2.6 mA I_{sc} for the van directly connected to earth. This measurement implies that the impedance of mc_1 is somewhere in the vicinity of 15 kΩ but more careful measurements are called for to accurately determine the true impedance.

A number of measurements of I_{sc} for individuals immersed in various field intensities were made with the person standing on a hot line blanket at a position beneath the 765 kV line where the unperturbed field gradient had been determined just prior to the tests (see Figure 20). The data obtained from this series of measurements is reported in Table 9. The height of each person (a total of three) is also shown. From each set of data an average normalized body current, I_{sc}/E, was computed and listed. This parameter expressed in μA/(kV/m) is seen to be approximately 18 μA/(kV/m) for individuals insulated from ground by standing on a hot line blanket. Similar measurements were taken with the individuals standing directly on the earth ground, and this data is seen in Table 10. The normalized body current in this case is about 17 μA/(kV/m). These measurements are in general agreement with others reported in the literature [4] and are a function of the person's height and shoe resistivity. No determinations were made of the distribution of this current in the body. When the field meter was held 9 inches above one person's head (see Figure 21), while he was standing in an unperturbed field of 10 kV/m, the field strength meter read 25 kV/m. This reveals the convergent properties of the field in the neighborhood of the conductive body.

Another interesting test was conducted to determine a person's threshold for perception and annoyance of transient spark discharge. Perception in these tests was defined as the person's ability to tell that a shock effect was occurring as he touched a ground rod driven into the earth. Annoyance was defined, subjectively, as a condition which the observer would not like to occur again. The results are tabulated in Table 11 where a coarse subjective rating scheme was used as follows: a (-) sign means not perceived, a (o) means perception was noted, and a (+) sign means the feeling had reached an annoying level.

Figure 20 Measurement of I_{gc} for an individual

Figure 3: Measurement of converged electric field strength above individual's head

Table 9

I_{sc} for Three Individuals as a Function of the Field Gradient
Individuals Standing on Hot Line Blankets

Subject	Height (ft-in)	Electric Field Gradient (kV/m) 2	4	6	8	10
A	6-3	38	76	110	140	190
B	6-1	38	73	110	140	180
C	6-0	35	68	105	135	170
Average I_{sc}(uA)/ E(kV/m)		18.5	18.1	17.8	17.3	18.0

Table 10

I_{sc} for Three Individuals as a Function of the Field Gradient
Individuals Standing Directly on Earth Ground

Subject	Height (ft-in)	Electric Field Gradient (kV/m) 2	4	6	8	10
A	6-3	36	72	110	140	160
B	6-1	36	71	100	130	160
C	6-0	33	68	95	120	150
Average I_{sc}(uA)/ E(kV/m)		17.5	17.6	16.9	16.3	15.7

The tests were made by first using the tip of one's index finger to touch a round head screw located near the top of each ground rod. Next the individual lightly brushed the back of his hand against the screw head as a perhaps more sensitive indicator. The results of these subjective tests indicated that in almost all cases persons could perceive the spark discharge produced between their body and ground when immersed in fields of 4 kV/m or more, if they were well insulated from ground. Generally, at field intensities of 8 kV/m or greater, the sensation was considered extremely annoying.

Table 11

Human Perception and Annoyance Tests
Transient Spark Discharge

Subject	Subjective Perception/Annoyance Rating E(kV/m)				
	2	4	6	8	10
A	o/-	o/-	o/o	+/o	+ /+
B	o/-	o/o	+/+	++/++	++/++
C	o/-	o/o	+/+	++/++	++/++
D	o/-	o/o	+/+	++/++	++/++

Rating symbols (-) no perception
(o) perception
(+) annoyance
(++) extremely annoyed

Back of Hand / Tip of Finger

A final test of perception was made using the so-called umbrella test wherein a person walks continually into a higher electric field strength holding the umbrella by the insulating handle and repeatedly touches the button just above the umbrella handle to allow spark discharge. The umbrella, being charged as a capacitor in the field, can create substantial reflex reactions, in contrast to the above tests, due to transient current flow through the person's thumb (see Figure 22). In these tests either the spark discharge was graded as OK, which meant tolerable, or NO which meant that the spark discharge was very uncomfortable and not desired again. This data is given in Table 12. Again a general threshold of about 6 kV/m was found to demarcate the levels below which individuals would accept repeated shocks from the umbrella and that level beyond which shocks were clearly disturbing and not desirable.

A test was made of the short circuit current available from a simulated wire fence strung parallel to the 765 kV overhead line outer phase bundle and approximately 3 feet above ground. The simulated fence consisted of 102.5 feet of copper antenna wire placed at a height corresponding to an unperturbed field gradient of about 10.2 kV/m. A measurement of 0.88 mA was made for I_{sc} to a ground rod. The spark discharge effect was very vivid, and painful, while the continuous current flow after the initial discharge was also unpleasant.

Figure 22 Perception testing with an umbrella

Table 13

Umbrella Perception Transient Spark Discharge

Subject	Electric Field Strength (kV/m)				
	3	4	5	6	10
A	OK	OK	NO	NO	NO
B	OK	OK	OK	NO	NO
C	OK	OK	NO	NO	NO
D	OK	OK	NO	*-	*-

Perception Rating - OK means subject could tolerate spark discharge on a repeated basis.

NO means subject would definitely not like to tolerate repeated discharge.

*Subject would not enter higher field strengths.

Near the completion of these tests a farm tractor was made available for measuring short circuit current under the 765 kV line. A value of 0.6 mA was measured but the shock effect was not nearly as severe as that created by the simulator fence which had a similar I_{sc} value. It is possible that the impedance of the tractor was low with respect to a human and consequently relatively little current was being conducted through the body. No body current measurements were taken to substantiate this observation.

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